Biomimetic Shark Olfactory Sensor Miniaturization

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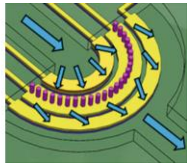
Abstract

To make the development of the electronics taking measurements from a microelectromechanical systems (MEMS) chemical sensor designed to mimic the morphology of the olfactory sensors in sharks more accessible, the electronics and code were simplified. This project further miniaturized the circuit that controls the biomimetic shark olfactory sensor using an Arduino Uno microcontroller, DAC, and potentiostat circuit to control a potentiostatic circuit that could perform experiments using both cyclic voltammetry and anodic stripping voltammetry.

Introduction

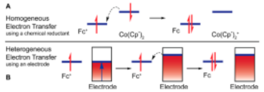
The design of the electrochemical sensor was developed by mimicking the structural morphology of olfactory sensors in marine animals. Wang Nan et al. designed and built a MEMS chemical sensor with an array of free-standing micropillar working electrodes with the goal of creating a more sensitive sensor by increasing the surface area of the working electrode and adding flow channels to eliminate the need to manually stir the solution.

This design imitates the morphological and functional benefits of the olfactory sensing capabilities of pelagic (open ocean) sharks. While flowing through the sensor, the solution must pass through an array of standing micropillars that are coated in the sensing martial. This greatly increases the effective sensing area that is in contact with the testing solution.


MEMS electrochemical sensor

One method for measuring the type and concentration of an analyte is through cyclic voltammetry. This method works through electrochemical reduction. Potassium Ferricyanide was used as the analyte for all of the voltammetric experiments.

Chemical Formula:
$[Fe(CN)_6]^{3-} + e^- \rightleftharpoons [Fe(CN)_6]^{4-}$

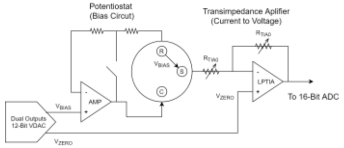


In cyclic voltammetry, an increasingly reducing potential is applied to the electrode. This triggers the reduction of analyte resulting in a current output. After this occurs the current will decrease as the concentration of reducible analyte goes down. When this is reversed, the reduced analyte will start to be re-oxidized, giving rise to a current of reverse polarity.

Electronics

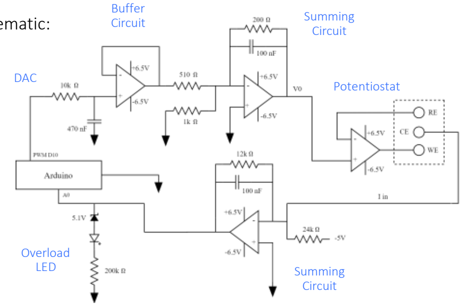
Previously, the Analog Devices EVAL-ADICUP3029 microcontroller and AD5940 Electro-chemical Shield were used in the electronics design because they incorporated everything needed for potentiostatic sensing. However, the electrochemical shield also came with a variety of unnecessary features. Additionally, the microcontroller could not save measurements in the long term and the circuit was not customizable. To address these issues, this project replaced this system with an Arduino Uno microcontroller and simple digital to analog converter and potentiostat circuits that could set the desired potential in a three-electrode electrochemical sensor.

A potentiostat circuit allows the potential of the working electrode to be set with respect to the reference electrode by adjusting the current at an auxiliary (counter) electrode. It does this by using a control amplifier that makes it so that the voltage over reference and working electrode is equal to the input voltage.



The current output of the sensor is a function of the resistance of the solution as described by ohm's law: $I = V_{BIAS}/R$

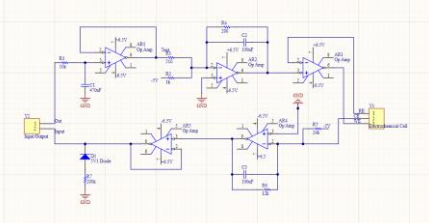
Schematic:



The peak current measurement can be described by the Randles-Sevcik equation: $I_p = kn^{3/2}AD^{1/2}C_b\upsilon^{1/2}$ Where The I_p is linearly proportional to the bulk concentration (C_b) of the electroactive species, and the square root of the scan rate ($\upsilon^{1/2}$). This can be used to calibrate the sensor

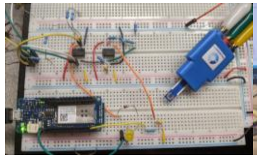
PCB

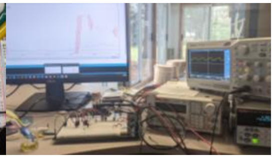
In order to make the device as compact as possible, the circuit would need to be printed on a printed circuit board. Altium Designer was used as the CAD software for the PCB. On a PCB, all the electronics can be condensed to around a square inch.



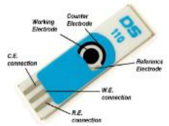
Experimental Setup

A prototype of this circuit was developed and tested on a breadboard,

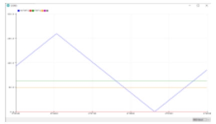




Simple screen printed electrodes were used in place of the bio-mimetic MEMS chemical sensor to test the new electronics. These electrodes were sourced from PalmSens.



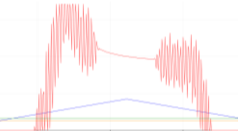
To generate the signal needed to perform cyclic voltammetry, a C program was written. Cyclic voltammetry uses a triangle wave signal to first to apply an increasingly reducing potential. However, the resolution of the PWM output on the Arduino is quite low so the frequency of the port needed to be adjusted.



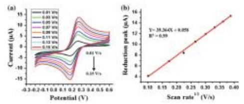
The code used in this design can be found with this QR code:

Measurements

$[Fe(CN)_6]^{4-}$ concentration: 10mM
Electrode type: Gold, Ø 1mm
Scan rate: 100mV/s



As analyte concentration increases peak current also increases. The peak current also corresponds to the voltage at which the analyte is reduced which can be used to identify the substrate.



The scan rate can also be adjusted to solve the Randles-Sevcik equation and calibrate the sensor. Additionally, the faster the scan rate, the higher the peak current.

Measurements can be saved to an SD card through an SD card shield on the Arduino Uno or over WiFi with the MKR1000 Arduino. Once the calibration process is complete, the measurements can be displayed on an LCD screen. One problem with the signal is the noise that occurs when the measurement is taken. A lot of this noise is caused by the fact that the circuit is on a breadboard. Another problem could be that the resistors on the DAC and buffer circuits might be off.

Next Steps

While the electronics for the electrochemical sensor have been miniaturized and simplified, further work can be done to finalize the design and improve usability such as printing the circuit on a PCB, making a casing for the sensor, and adding a display for reading measurements. Additionally, noise reduction measures should be taken to take more accurate measurements. The signal should also be modified to take measurements of metal ions using Anodic Stripping Voltammetry. Test the sensitivity, resolution, stability, accuracy, and power consumption of the entire system. Possible applications of this work include developing sensors for underwater robots that track chemical plumes and follow a chemical spill to its source, as well as low-cost but highly sensitive sensors for portable environmental monitoring instruments.

Acknowledgements

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Elgrishi, Noémie, et al. "A Practical Beginner's Guide to Cyclic Voltammetry." Journal of Chemical Education, vol. 95, no. 2, 2017, pp. 197–206., doi:10.1021/acs.jchemed.7b00361.
Borrill, Alexandra J., et al. "Addressing the Practicalities of Anodic Stripping Voltammetry for Heavy Metal Detection: a Tutorial Review." The Analyst, vol. 144, no. 23, 2019, pp. 6834–6849., doi:10.1039/c9an01437c.
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